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UPDATE ON THE PALEOGENE WATER-LEVEL DRAWDOWN HYPOTHESIS, GULF OF MEXICO

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ABSTRACT

We provide an update on the Gulf of Mexico Paleogene water-level drawdown hypothesis by revising and augmenting the original observations to provide new grounds for the continuing assessment of this concept, which has important implications for hydrocarbon exploration. This paper assimilates information on 7 issues from a variety of sources that suggests attention should be focused on the 56 Ma sequence boundary as the most likely time of drawdown, just before the Paleocene-Eocene Thermal Maximum (PETM), rather than mid-Paleocene as was first thought. The younger timing downplays the possible association between the Paleocene "Whopper Sandstone" and drawdown, and provides the time necessary for the Cuban Arc to begin collision with the Bahamas Platform and close the Florida Straits, a necessary part of the hypothesis. We highlight data from other authors that appear to show that the fastest rate of clastic deposition for all Wilcox time was at about 56 Ma. We also focus on evidence that there may have been Paleogene evaporative conditions in the Gulf, and whether evaporites are even necessary for the viability of the hypothesis. We highlight and discuss evidence from a selection of more than 33 paleo-canyons around the Gulf rim, most of which could have been formed at ~56 Ma given current dating, and we consider the apparent formation of a Gulf-wide unconformity at this time, just before the PETM. The magnitude of the proposed drawdown is estimated from evidence along the thalweg of the Chicontepec paleo-canyon in eastern Mexico. Evidence for subaerial exposure and erosion along the margins of western Florida and northern Yucatán, including at Chicxulub, is also reviewed. Finally, the enigmatic Georgia Channel System is highlighted, and we call for detailed work to confirm if short-lived interruptions in circulation between the Gulf and the Atlantic Ocean during the Paleogene might have occurred, particularly at ~56 Ma. Another good thesis topic would be to deconstruct the last stages of the Cuban orogen and further test the required continuity of a land bridge from southern Florida to Yucatán at ~56 Ma, using comprehensive seismic and well databases in the Yucatán and Florida Straits and the western Bahamas.

INTRODUCTION

The Paleogene water level drawdown hypothesis for the Gulf of Mexico Basin was advanced by Rosenfeld and Pindell in 2003 as a possible unifying explanation for a number of geological observations that were otherwise difficult to understand. A short-lived reduction in water level of 1–2 km was proposed to have been caused by isolation of the Gulf from the world ocean during Paleocene–early Eocene time by the collision of the Cuban Arc with the southern Bahamas, creating a subaerial landmass crossing from Florida to eastern Yucatán Peninsula. The hypothesis has been received with positive and negative viewpoints. While we acknowledge the need for revision of some of the original aspects of the hypothesis, several of the negative viewpoints seem to be founded in misunderstanding or misperception.

Rosenfeld (2019, 2020) highlighted some of the historical and more recent geological observations around the Gulf of Mexico that point to a possible short-lived episode of drastic water level drawdown in the Paleogene, similar to the Messinian drawdown in the Mediterranean (Ryan, 2009). Several lines of evidence suggest a magnitude of drawdown that far exceeds any feasible eustatic fluctuations, and thus the event has been linked to the basin's suspected isolation from the world ocean as a result of the Cuban Arc–Bahamas collision temporarily closing off the

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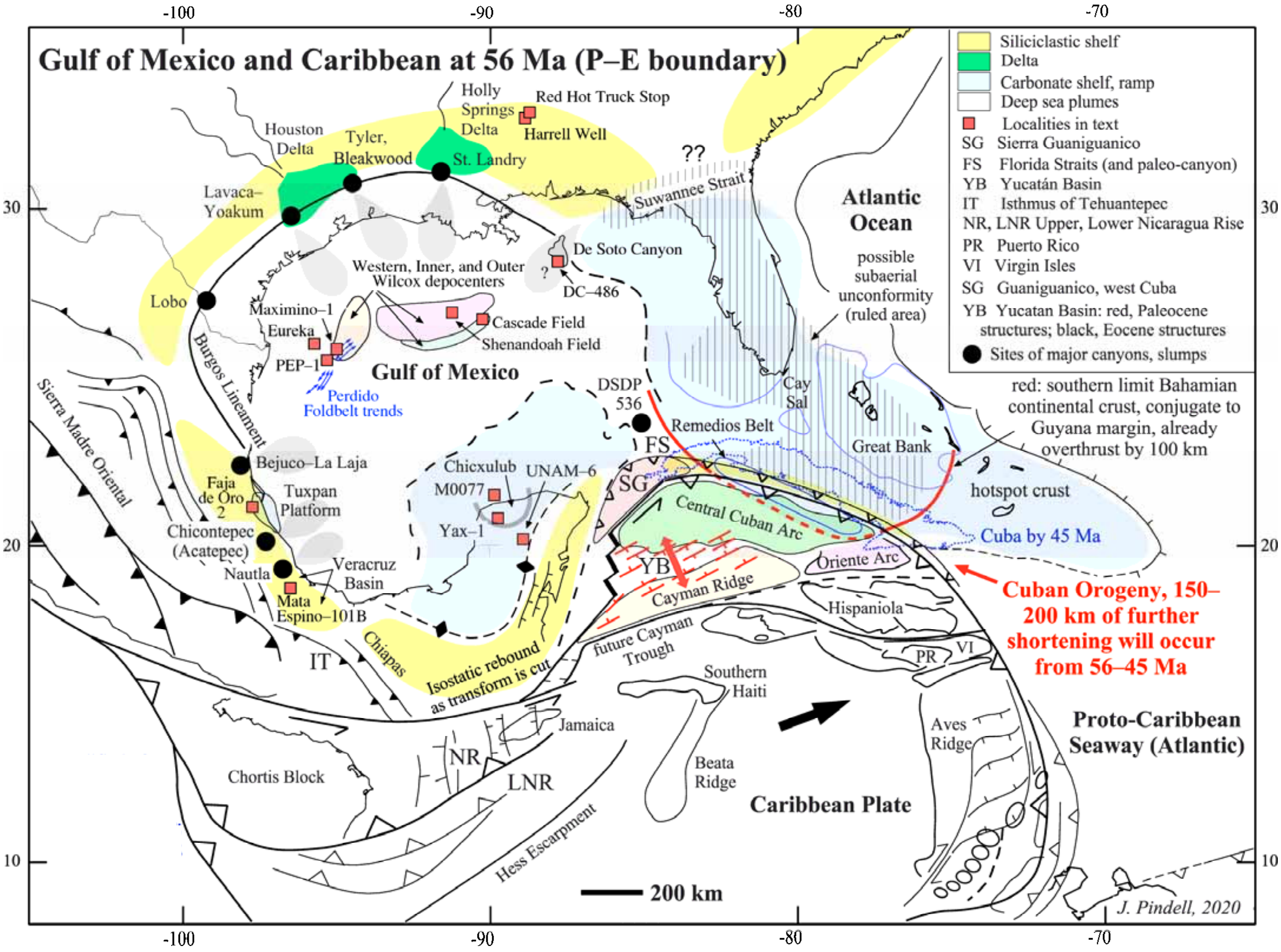

Figure 1. Gulf of Mexico and Caribbean at the 56 Ma most likely time of drawdown in the Gulf of Mexico, with localities cited in text (modified after Rosenfeld and Pindell, 2003; Rosencrantz, 1990; Pindell et al., 1988, 1998, 2005). The Cuban Arc/prism had begun obduction onto the shallow-water "Remedios Belt" defining the southern edge of the Bahamas Platform, imbricated within Cuban thrust sheets after 150–200 km of further shortening.

Florida Straits (Rosenfeld and Pindell, 2003). Along with many of the localities mentioned herein, Figure 1 shows the geological setting of this collision across the Florida Straits based on the more regional history of the advance of the Caribbean Plate between the Americas (Fig. 2) and the belief that Cuba has overthrust the southern fringe of the Bahamas Platform by about 100 km (Moreno-Toiran, 2003; Pindell et al., 2020).

One of the most economically important aspects that might pertain to the drawdown hypothesis in the Gulf concerns the deposition of parts of the deepwater Paleocene–Eocene Wilcox Group reservoirs in the deep basin, in which tens of billions of barrels of oil and associated gas are expected to be found (Meyer et al., 2005). Another is the interpreted deep meteoric karsting and secondary reservoir development of carbonate platform strata around the Gulf, such as those of the Tuxpan Platform in eastern Mexico (Horbury et al., 2003).

Numerous lines of evidence for drawdown were noted by Rosenfeld and Pindell (2003), as well as the potential isostatic effects of the drawdown (unloading of water) and refilling (reloading of water) on the Gulf margins. Much of the evidence for drawdown remains uncontested, while some has been met with doubt.

Arguments against the drawdown hypothesis were recently summarized by Snedden and Galloway (2019) and Snedden et al. (2020), who portrayed Wilcox time in the Gulf as a period of normal marine pelagic and turbiditic deposition that requires no drawdown to understand. These authors pointed to differences in the ages of certain geological features that were thought by Rosenfeld and Pindell (2003) to be temporally related. They argued that deepwater Wilcox sedimentology and oil geochemistry showed no signs of evaporative conditions as was posited in the original hypothesis. Further, they considered that the erosional style and presence of sink holes and steep-sided canyons in deep water today along the Florida and Yucatán shelf edges and escarpments, put forth as new arguments for drawdown by Rosenfeld (2019, 2020), were not directly indicative of subaerial exposure. Sweet and Blum (2011) also argued against drawdown, focussing on the issues of timing of possible connection to the Atlantic Ocean via the Suwannee Strait and the otherwise "normal" dimensions of the Wilcox fans compared to the large rivers which could have produced them. Still another concept was presented by Higgs (2009), stating that marine isolation must have occurred, but that fluvial input *exceeded* evaporation while the Gulf was isolated, such that the Gulf became brackish

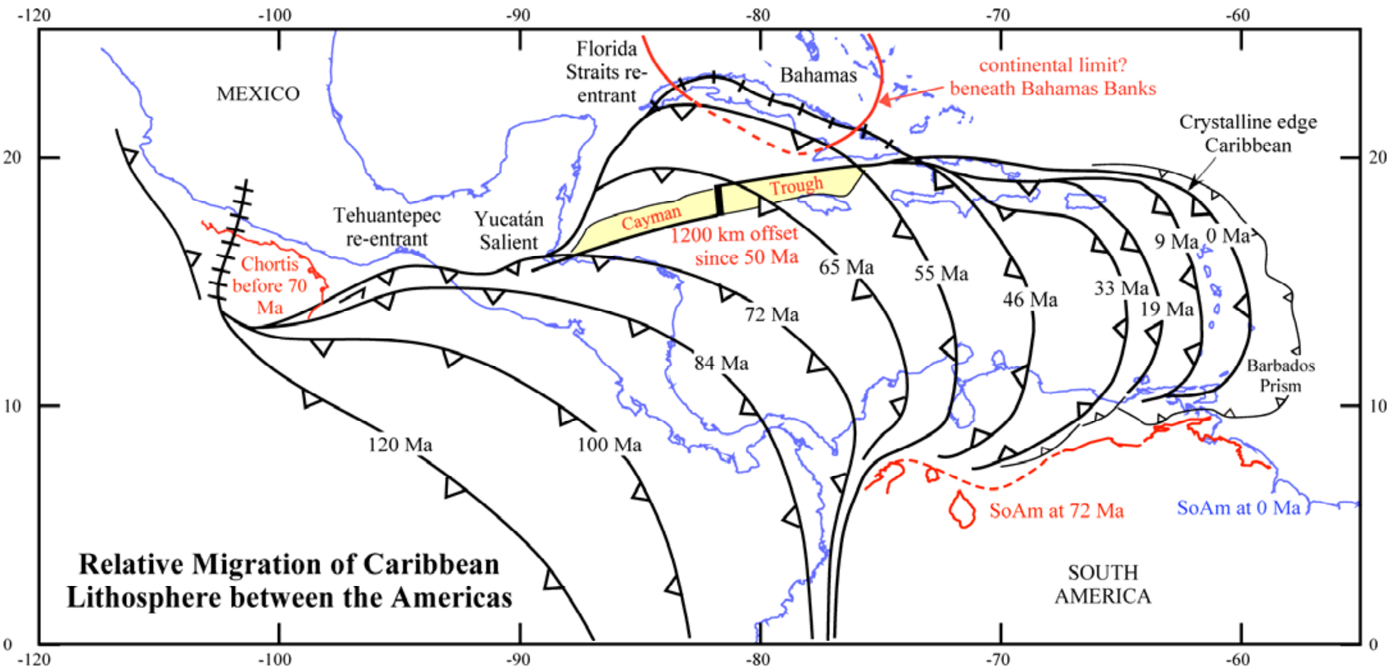

Figure 2. "Sweep of the Antillean Arc of the Caribbean" between the Americas, modified after Pindell and Barrett (1990), Pindell and Kennan (2001, 2009), and Pindell et al. (2005, 2006). Relative motion is actually driven by westward drift of the Americas over the mantle; Caribbean has been stationary in the mantle reference frame for most of the Cenozoic. Cayman Trough began to open in the Eocene, thereby stranding Cuba and the Yucatán Basin with the North American Plate and allowing the rest of the Caribbean to move relatively east without them.

during Wilcox time causing the poor development of Wilcox fauna.

This paper provides an update on the present status of old and new arguments, expands on the recent article by Pindell and Cossey (2020), and revises the original proposed hypothesis of Rosenfeld and Pindell (2003) with added evidence to clarify the current perception of the timing and nature of a Paleogene drawdown in the Gulf of Mexico. Much of the update stems from ongoing efforts to test the problem since 2011 as a task in the ongoing industry-sponsored Cordilleran Mexico–Gulf of Mexico work program by Tectonic Analysis Ltd., and from over 16 yr of fieldwork in eastern Mexico as reported by Cossey et al. (2016, 2019). Below, we highlight 7 issues concerning the drawdown hypothesis in order to provide an updated perspective on the feasibility of this pivotal hypothesis. We then discuss the possible implications of the suspected drawdown on the deep Gulf Basin fill of the Wilcox Group.

1. PALEOGENE EVAPORATIVE CONDITIONS IN THE GULF?

The majority of arguments for drawdown can be explained with a relative water level fall of 1 to 2 km. Thus, we now consider that if Paleogene drawdown due to marine isolation occurred, then: (a) some 3–4 km of water always remained present in the deepest part of the Gulf Basin assuming an original Paleocene paleo-depth in the deep Gulf of about 5 km, as estimated by oceanic subsidence models and sediment thicknesses prior to the majority of Cenozoic clastic infilling; and (b) that fluvial input relative to evaporation was sufficient to avoid episodes of severe desiccation, except in the basin margin areas. Thus, in agreement with Sweet and Blum (2011), Snedden and Galloway (2019), and Snedden et al. (2020), we do not expect voluminous evaporites, shallow marine or subaerial facies in the deep Gulf Basin, we accept the observed scaling relationships between large rivers and run-out lengths of turbiditic fairway systems, we do not expect evaporative signatures in Wilcox-sourced oils, and we do not expect turbiditic and pelagic deposition ever to have ceased in middle to lower slope and abyssal settings of the Gulf. Periods of potential drawdown may only represent a small part of overall Wilcox time.

That being said, an occurrence of Paleogene evaporites has been recorded in a well in the Yucatán Peninsula, Mexico. The UNAM–6 well (Fig. 1) is located outside the Chicxulub impact crater and cored about 27 m of anhydrite and gypsum of lower Eocene age (Lefticariu et al. 2006). According to Rebolledo-Vieyra et al. (2000), the evaporites in the UNAM–6 core were deposited on a probable depositional polymictic breccia formed during the Paleocene due to subaerial exposure (Lefticariu et al. 2006, their p. 55). Because this evaporite seems to be limited to the Yucatán Platform, it is unlikely to pertain to a Gulf-wide evaporative event. Instead, the UNAM–6 well probably occupied a restricted, lagoonal setting surrounded by an intermittent barrier to the sea where evaporites were fed by Gulf water for a time. Nevertheless, both the polymict breccia and the evaporite may relate to a Paleocene-Eocene boundary drawdown, as the depositional setting for the platform was generally deeper in the Paleogene than coastal-inner neritic (López-Ramos, 1975).

Groundwater salinities of the Wilcox Group may also hold a clue to whether the depositional system during the Eocene may have been different from that in the Paleocene. In a detailed study of water salinities in the Wilcox of SE Texas, Moran (2003, their p. 133) concluded that there is a cell of fresh water in the Upper Wilcox and that "it is possible that some meteoric water may have entered the area during a short-lived regression after the Eocene." Hamlin and De la Rocha (2015) also confirmed a similar freshwater cell to depths of greater than 1500 m below the surface in the Upper Wilcox of South Texas. It grades downdip into brackish groundwater without intervening flow barriers but is hydraulically separated from brackish groundwater in the

Lower Wilcox. In Mexico, limited data from water samples in Wilcox wells show a dramatic difference in salinities between the Eocene and the Paleocene sections. In the PEP–1 well in the Perdido fold belt area of Mexico (Fig. 1), the Eocene formation waters had salinities of 19,000 ppm but the Paleocene formation water had a salinity of 80,500 ppm (Pemex personal communication, 2014). In the Maximino–1 well (Fig. 1) the lower Eocene formation waters had a salinity of 21,382 ppm. Sea water “normal” salinity is considered to be 35,000 ppm (https://en.wikipedia.org/wiki/Seawater). Could this Eocene brackish formation water pertain to a decrease in Gulf Basin salinity and long-duration, hyperpycnal turbidity currents as proposed by Higgs (2009)? Regional water salinity studies may provide us with clues to this possibility.

Lastly, syneresis cracks (indicative of salinity changes) have been reported from Paleogene levels of the Cascade (Wilcox 2) and Shenandoah fields (well WR52–2BP1 core #1 at ~9750 m) in the inner and outer Wilcox depocenters (Fig. 1), and sidewall cores from early and middle Eocene section in the fields producing from the Chicontepec Formation in east-central Mexico (Popote, Tablón, and Humapa fields) locally contain up to 5% gypsum, as does the ~56 Ma interpreted paleosol within the mainly bathyal Chicontepec Formation (Cossey et al., 2019, their figures 11 and 12). Whether this type of information might pertain to a drawdown and basinal change in Gulf salinity is unknown.

2. PALEO-CANYONS ALONG THE GULF MARGIN

Eastern Mexico Paleo-Canyons

More than 33 paleo-canyons and slide complexes have been identified in the Gulf of Mexico rim since the early 1980s (Table 1). Some of these have been studied in great detail (e.g., the Yoakum and the Chicontepec paleo-canyons) and some have only been mentioned briefly in the literature. Little accurate age dating has been conducted on most of these paleo-canyons, but the age of formation of two thirds of the known examples can be estimated. Of these examples, at least 19 could have erosional ages of about the Paleocene-Eocene boundary (56 Ma; Ogg et al., 2016). In order to estimate the age of incision, one can trace the erosional surface up to the uneroded section at the margin of the canyon where a more complete section is preserved. Additional-

Table 1. Compilation of information (e.g., scale, age, timing of incision) on more than 34 paleo-canyons and slide features known to exist around the Gulf of Mexico. Red text in column A represents a large slide or slump event. Bold underlined text in column A are the longest canyon systems. Sources for each as shown. Column F is our interpretation of which features could have been formed at 56 Ma, where red color = younger or older than 56 Ma event, orange = possible 56 Ma event, and green = 56 Ma event.

Canyon or Feature (Florida to Yucatan)	**Approx Age of Erosion (Ma)**	**Length (km)**	**Width (km)**	**Max Fill Thickness (m)**	**56 Ma Event?**	**Main References**
Florida Strait Canyon	50–57				YES	Denny et al. (1994); Buffler et
West Florida Escarpment canyons	post-Cretaceous	up to 50 km	up to 5 km	Little or no fill	POSSIBLY	Rosenfeld (2019)
St. Landry, LA	58–59?	>65	4–17	300	YOUNGER?	McCulloh and Eversull (1986)
MEA Canyon, LA	Upper Wilcox	>80	12–13	1463	POSSIBLY	Watkins (2014); F. Vincent (2020, pers. comm.)
Beauregard Parish, LA	Mid-upper Wilcox	>30	3–4	>215	POSSIBLY	T. Rynott (2019, pers. comm.)
Bleakwood, TX					?	Galloway et al. (1991)
Tyler (Hardin), TX	Upper Wilcox	>42	3–8	500	POSSIBLY	Hutchinson (1987); Cornish (2019)
Lavaca, TX	60.4				OLDER	Snedden and Galloway (2019)
Halletsville Slump Complex, TX		40	142		OLDER	Devine and Wheeler (1989); Clayton (2017)
Yoakum, TX	56	>129	7–20	1067	YES	Snedden and Galloway (2019); Galloway et al. (1991)
Hope, TX	49–56				POSSIBLY	Cornish (2013)
Jennie Bell, TX	49–56	24		240	POSSIBLY	Cornish (2011, 2013); Cornish and Lambiotte (2016)
Anna Barre, TX	49–56	20		232	POSSIBLY	Cornish (2013); Cornish and Lambiotte (2016)

Table 1. Continued

Canyon or Feature (Florida	**Approx Age of Erosion (Ma)**	**Length (km)**	**Width (km)**	**Max Fill Thickness (m)**	**56 Ma Event?**	**Main References**
Meyersville, TX	49–56	20			POSSIBLY	Cornish (2013); Cornish and Lambiotte (2016)
Goliad Co. canyons, TX					?	Cornish (2013)
McCaskill Canyon, TX		16	4–5		?	F. Cornish (2020, pers. comm.)
Lobo slides	before 60.5 Ma				OLDER	Long (1986)
Rio Grande/Rio Bravo		>600?			OLDER?	Fernández Turner (2006)
Bejuco–La Laja	56	>100	10–60	2000	YES	Cantú Chapa (2001); Carillo-Bravo (1980); O'Reilly and Keay (2020); Araujo (1978)
Acatepec*	56	26	20		YES	Cossey et al. (2019)
Miquetla Slide, Tampico-Misantla Basin					YOUNGER	Pemex (2012, pers. comm.)
Llano Enmedio*	56	8	5		YES	Cossey et al. (2019)
San Lorenzo*	56	29	7		YES	Cossey et al. (2019)
Cazones*	56	28	17	140	YES	Castro and Rivera (1984)
Chicontepec	56	200	23	>800	YES	Cossey et al. (2019); Busch and Govela (1978); Cantú Chapa (2001)
San Andres	Cretaceous				OLDER	Cantú Chapa (2001)
Nautla*	56	30	15	2500?	YES	Cossey et al. (2019); Castro and Rivera (1984)
Paso de Ovejas					?	Castro and Rivera (1984)
Papaloapan	23–56	40	20		YES	Castro and Rivera (1984); Carillo Bravo (1980)
Coatzacualcos					?	?
Grijalva-Usumacinta					?	?
Tomón		>66	16		?	Carillo Bravo (1980); Castro and Rivera (1984)
Akal (and Chilán)		90	8		?	Castro and Rivera (1984); Carillo Bravo (1980)
Campeche Escarpment canyons			10	820–1200	POSSIBLY	More than 14 canyons; Carillo Bravo (1980)

* = tributaries of the Chicontepec paleo-canyon

ly, the oldest age of the canyon fill can bracket the youngest age of the incision, assuming that reworking of sediments is minimal enough to allow an accurate age to be determined.

The longest paleo-canyon systems (MEA, Yoakum, Bejuco-La Laja, and Chicontepec; Table 1) could have been eroded at 56 Ma. Recent seismic profiles across the Bejuco–La Laja paleo-canyon (O'Reilly and Keay, 2020) and published cross-sections (Araujo, 1978) show it to have been formed close to the Paleocene-Eocene boundary with incision down into the Jurassic section.

There are some features that are clearly older than 56 Ma such as the Lavaca paleo-canyon, Texas, thought to represent a shelf edge failure, and a small number that are younger (St. Landry, Louisiana; McCulloh and Eversull, 1986). Current knowledge summarized in Table 1, however, indicates the larger, sinuous paleo-canyons could all have been formed at about 56 Ma. Shorter features that are more likely shelf-edge failures include the Hope, Jennie Bell, Anna Barre, and McCaskill paleo-canyons (Table 1), rather than truly incised systems. Shelf-edge failures generally form during the falling stages of a regression in areas away from major fluvial input (Armentrout, 1987). A few shelf-edge failure complexes occurred during the Wilcox time period (~51 Ma to 66 Ma, Ogg et al., 2016) (Table 1).

Several of the Paleogene paleo-canyons in Mexico have the advantage over their U.S. cousins of being exposed for field study and sampling (Fig. 1). The Chicontepec paleo-canyon complex in eastern Mexico comprises 6 tributary canyons, most of which can be studied in outcrop (Cossey and Bitter, 2020). Vásquez et al. (2014) and Cossey et al. (2016, 2019) presented a wealth of information about previously unmapped outcrops, concluding that the upper bathyal strata (estimated as 200–600 m paleo-water depth) hosting the canyons had been incised subaerially over 100,000–800,000 yr of canyon development at about 56 Ma. The canyon complex is unusual in many ways: It is extremely long (>200 km), makes at least two major directional changes, and follows the basin-axis—all atypical of submarine-cut canyons. Additionally, the most proximal outcrops of the canyon are incised into bathyal turbidites instead of shelf sediments, certainly not typical of a submarine canyon. Understanding the paleo-canyon is important because the mass transport complexes (MTCs) just above the basal Paleocene-Eocene unconformity (sequence boundary [SB] 56: Figure 3) appear to act as the seal for many of the Cenozoic fields in the basin.

A cross-section along the entire paleo-canyon thalweg (Fig. 3) shows that the gradient today averages 0.5° in the upper reaches (northwest of Nirzan–1 well) and 2° in the lower reaches. The cross-section also confirms that there is over 2500 m of stratigraphy missing (1000 m of Paleocene and 1500 m of Cretaceous) due to erosion in about 180 km of this section from the western outcrops to southeast of the Carmen–1 well (Fig. 3). A detailed portion of the paleo-canyon to the southwest of Poza Rica (see yellow box in Figure 3) shows that the steepest part of the thalweg is about 6° for more than 10 km (Fig. 4), where an 800 m thickness of stratigraphy has been eroded. The Chicontepec paleo-canyon is unlike typical submarine-cut canyons which are no steeper than about 3° and are generally steeper in the upper reaches than in the lower portions (Oiwane et al., 2011). In addition, submarine-cut canyons typically widen basinward (Dobbs et al., 2019) but the Chicontepec paleo-canyon narrows basinward.

It is also unclear where the shelf-edge was at the time of formation of the canyon. Gravitational slides (usually seen basinward of the shelf-edge) in the younger sequences (SB 46 to SB 56 and SB 46 to SB 38; Fig. 3) indicate that the shelf-edge must have been up-canyon of the Jano–1well (Fig. 3). From this we conclude that the majority of the erosion was basinward of the shelf-edge, again an observation not seen in other submarine-cut canyons.

Detailed 3D seismic mapping of the Paleocene/Eocene unconformity (Pemex, 2006, personal communication) has also revealed a terrace just above the top Cretaceous contact and numerous circular depressions within the subcrop of the Cretaceous carbonates, possibly caused by karstification (Fig. 4). In fact, porosities of up to 20% in the Antares-1 well located near the Nirzan–1 well (Fig. 3) appear to have been enhanced by dissolution up to 25 m below the SB 56 unconformity level (Pemex, 2008, personal communication). Cross-canyon profiles of the canyon in this area (Fig. 4) show it to be strongly asymmetric, with a well-defined terrace on the northeastern flank. The steep western side of the canyon was exaggerated during post-deposition deformation by the thrusting of the Cretaceous section from the west during the Laramide Orogeny (Gray et al., 2001). If reconstructed by flattening on the top of the Cretaceous, the cross-canyon profile is strongly terraced on both sides and the aspect ratio is about 33.3 (Fig. 4).

Interpretations favoring the fluvial origin viewpoint include the following:

(a) Bitumen was interpreted by Cossey et al. (2019) to have seeped subaerially onto parts of Chicontepec paleo-canyon terraces, where it is overlain by interpreted paleosols. Limonite tubes below the bitumen are interpreted as evidence for paleo-root systems just prior to the seeping of the bitumen layer. Upwards, the overlying turbidite deposits are classified as upper bathyal (Cossey et al., 2019) and appear to denote a rapid return to relatively deepwater marine conditions.

(b) In the Tampico-Misantla Basin, Cossey et al. (2019) describe outcrops approximately 100 m stratigraphically above one of the bitumen beds which have been interpreted as hypogene karst formed by ascending water where flow migrated up fractures and then spread laterally at a permeability contact that caps the soluble horizon (K. Stafford, 2020, personal communication). The karsting occurs within upper bathyal, lowermost Eocene calciturbidites, prior to Laramide (Eocene) folding (Fig. 5). This begs the question of why large volumes of water are being expelled upwards through lithified or semi-lithified turbidites, unless the water depth (and hence overlying pressure) has been reduced dramatically. Other evidence of water escape on a massive scale is preserved in the Junior–1 well in the Tampico-Misantla Basin (Fig. 3, between the Oberon–1 and Deimos–1 wells) where an over 7 m thickness of sediments containing water escape structures and sedimentary injection features have been described in core #6 by the senior author.

(c) Galloway et al. (1991) identified dip reversals in the thalweg of the Yoakum paleo-canyon which might indicate plunge pools. Hanging valleys and terraces are described within the Yoakum paleo-canyon (Chuber, 1986) that we consider may be uniquely fluvial features.

(d) A chronostratigraphic analysis from well data presented by Cornick et al. (2019) documented numerous hiatuses within the offshore Wilcox, with an estimated 50% of geologic time missing in some wells. A particularly prominent unconformity occurs immediately below the Paleocene-Eocene Thermal Maximum level (PETM) in many offshore wells. In the onshore upper bathyal Chicontepec Formation, Vásquez et al. (2014) portrayed four basin-wide unconformities at 38, 46, 54, 60.4 Ma; collectively, more than half the rock record is missing. The 54 Ma unconformity could be judged 56 Ma on updated (Ogg et al., 2016) timescales.

Additionally, in a basin-wide study of the stratigraphy, Diaz Cadenas (2008) identified four major sequence boundaries in the Chicontepec Formation at mid-Paleocene, top Paleocene, early Eocene, and mid-Eocene, which may correlate to the four unconformities identified

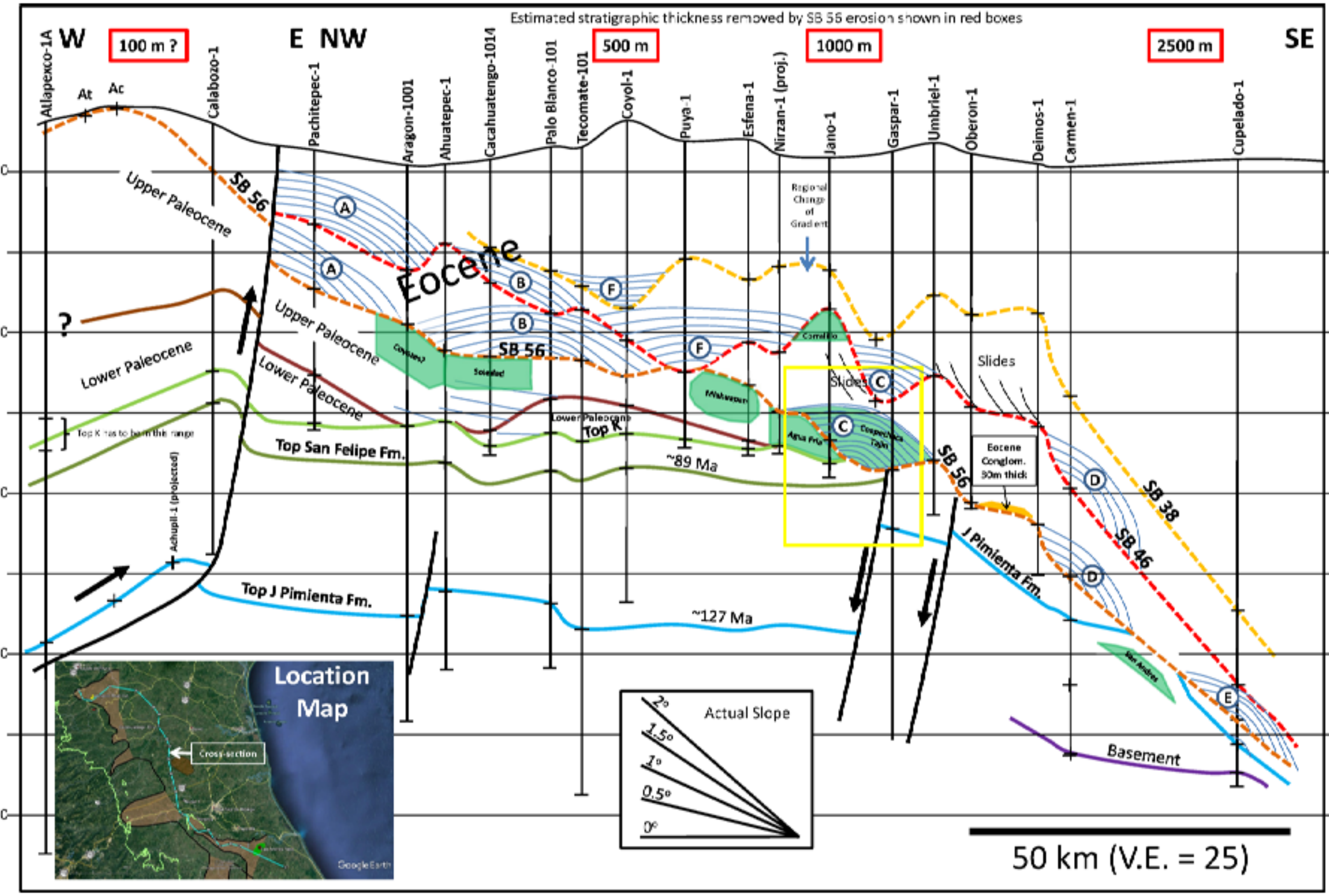

Figure 3. A 200 km long cross-section using well data (and seismic as a guide) along the thalweg of the entire Chicontepec paleo-canyon in eastern Mexico. Eocene unconformities (SB 56, SB 46, and SB 38) are shown in dashed lines and plotted from data derived from Vasquez et al. (2014). At = Atlapexco outcrop and Ac = Acatepec outcrop (Cossey, 2007; Cossey et al., 2019). Thin blue lines are onlap and downlap confirmed by seismic data. Bimodal downlaps A–E are the early Eocene fans described in Vasquez et al. (2014). Green shading are areas of known hydrocarbon production. Note the change of regional dip from about 0.5° to 2° between the Nirzan–1 and Jano–1 wells. Estimated thickness of stratigraphy eroded along the thalweg at about 56 Ma is shown at the top of the figure. Yellow box shows location of Figure 4.

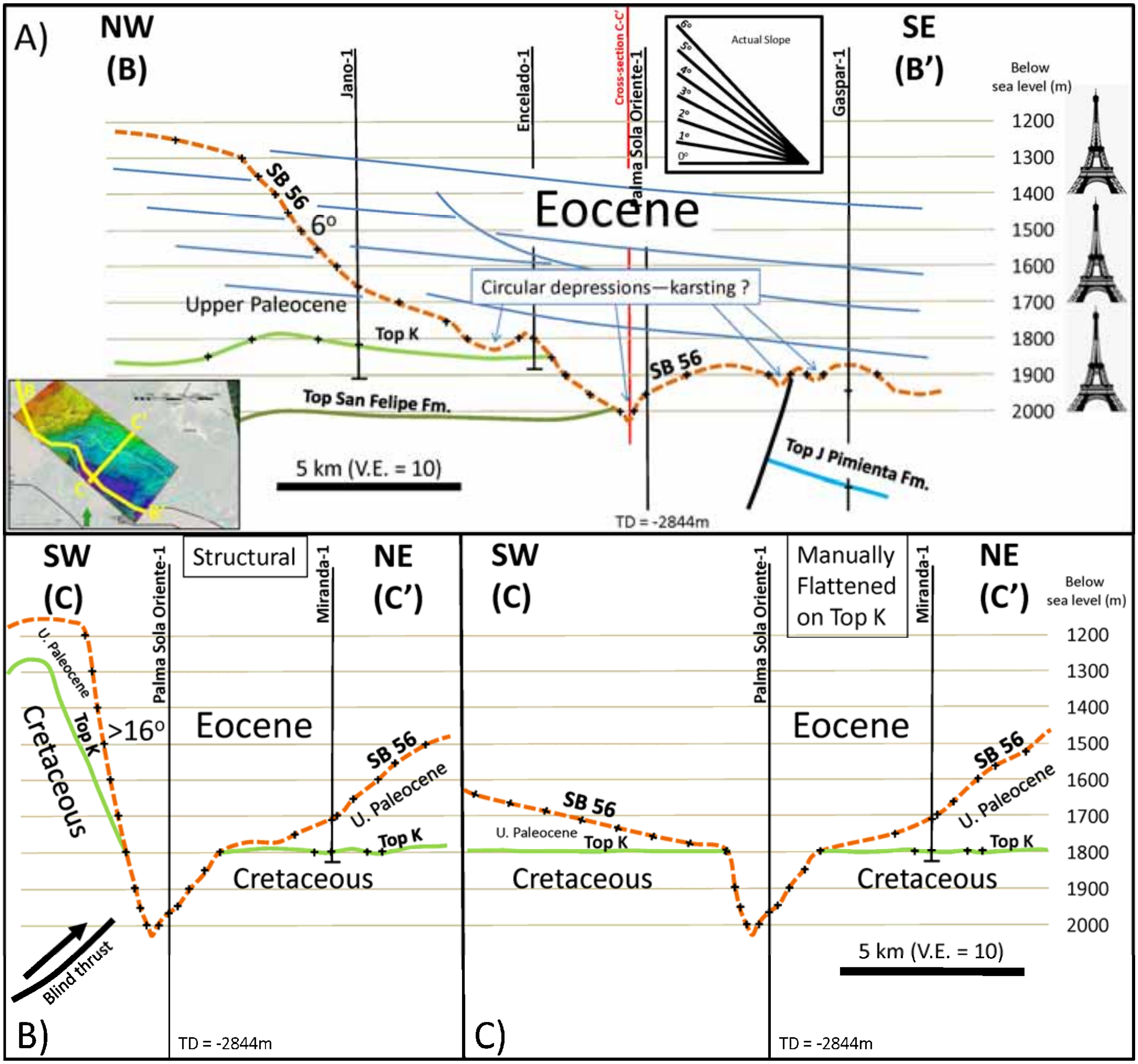

Figure 4. Details of Paleocene-Eocene unconformity (SB 56 Ma) along the Chicontepec paleo-canyon thalweg within yellow box shown on Figure 3. (A) Upper cross-section (B–B') is along thalweg and shows erosional slope within the thalweg is up to 6°. Paleo-topographic character is influenced by the change in lithology from less-resistant upper Paleocene turbidites to lithified Cretaceous carbonates. Note the first circular depression in the upper Paleocene sediments could be a plunge pool and three other circular depressions are interpreted to be karsted Cretaceous carbonates. Thin blue lines are onlaps and truncations confirmed by seismic and well data. (B) Cross-section C–C' shows the present-day structural configuration across the canyon with steep (16°) western flank. (C) The same cross-section C–C' flattened on the top Cretaceous showing the more symmetrical yet stepped canyon profile. Eiffel tower shown as a scale comparison.

by Vásquez et al. (2014). The mid-Paleocene horizon is an onlap surface, but the other three could be unconformities created by repeated drawdown events.

(e) Cornish (2013) described a series of 150 m clinoforms deposited on the erosional base of the Anna Barre paleo-canyon (Table 1) which are 5 km from the contemporaneous shelf edge and formed between 49 and 56 Ma. He interpreted these as a shelf-edge delta deposited during lowered sea level, considerably below the former shelf-edge. Is this evidence of a type–1 sequence boundary, i.e., a severe regression beyond the shelf edge in the early Eocene?

The Lavaca and Yoakum Paleo-Canyons, Texas

The Yoakum is one of the longest documented paleo-canyons on the rim on the Gulf of Mexico. It is over 130 km long and may have been even longer since the upper end of the canyon has been removed by erosion (Table 1). The amount of erosion along the curved thalweg is shown by Snedden and Gal-

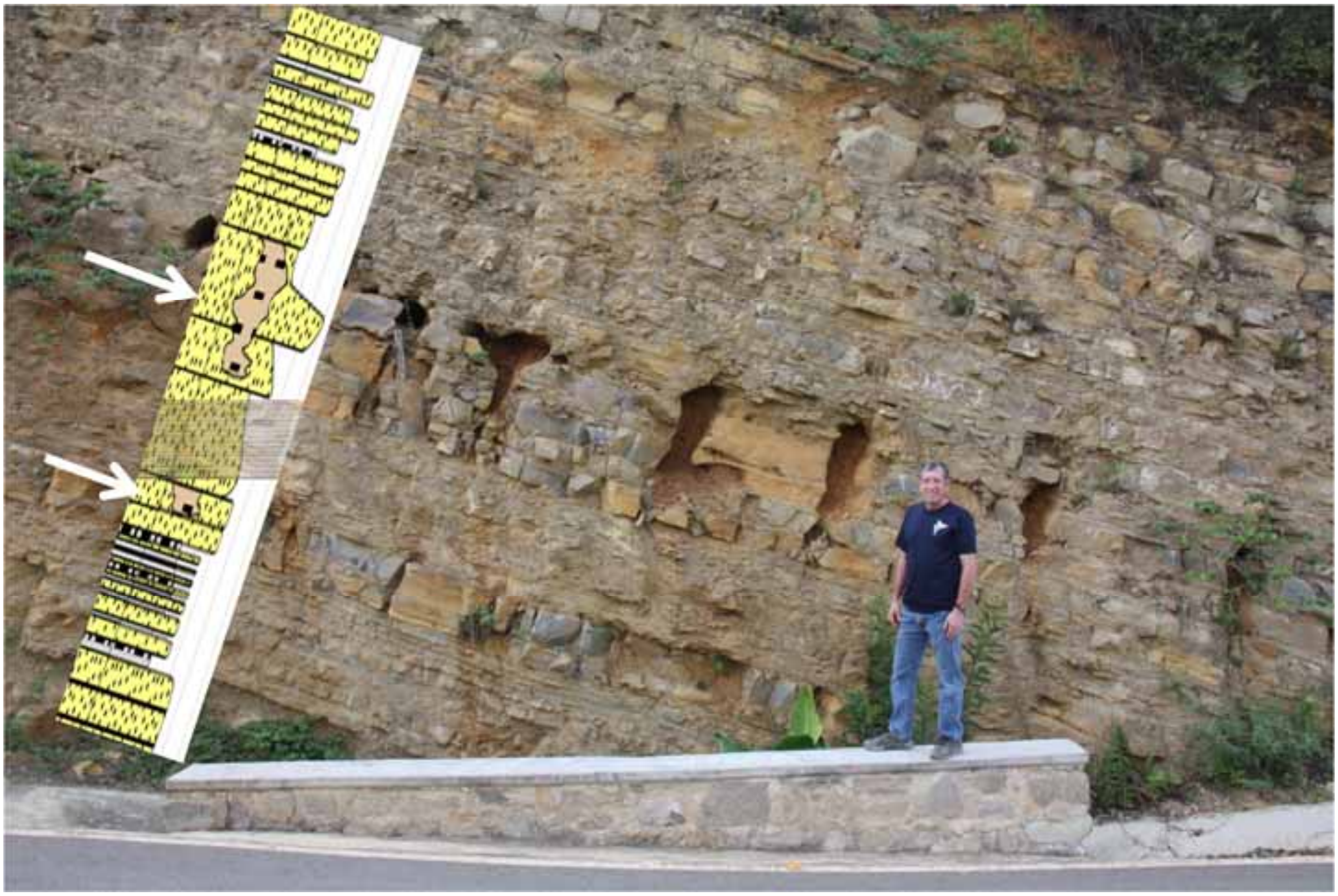

Figure 5. Interpreted hypogenic paleo-karst in the lower Eocene, upper bathyal, carbonate turbidites of eastern Mexico. This outcrop is at the Acatepec outcrop (Cossey et al., 2019) ~100 m above the Paleocene-Eocene boundary and may indicate large volumes of water moving upwards in the basin in the early Eocene. We thank Prof. Kevin Stafford for sharing his views on the nature of the karst.

loway (2019) to be considerably more than 915 m. It is commonly perceived that the older Lavaca "canyon" represents a mega-slump of the paleo-shelf edge assigned an age of about 60 Ma (Snedden and Galloway, 2019), whereas the Yoakum paleo-canyon cuts through the Lavaca and denotes deeper and more focused channel incision at 56 Ma (Fig. 6). We judge that the Yoakum paleo-canyon was formed just before the PETM because it incises the Middle Wilcox section, and the backfilled Yoakum Shale corresponds "closely with the Paleocene-Eocene boundary" (Snedden and Galloway, 2019, their p. 178). Thus, the timing of formation of the Yoakum and Chicontepec paleo-canyons correlate to the accuracy of current dating.

3. EXAMPLES OF OTHER LOCATIONS OF THE 56 MA UNCONFORMITY

Gulick et al. (2017) reported that the PETM at the continuously-cored Integrated Ocean Drilling Program (IODP) Chicxulub peak-ring (end Cretaceous bolide impact site: well site M0077; Fig. 1) is marked by a black shale, barren of fauna and about 24 cm thick. This overlies an unconformity and a 7.5 cm thick carbonate hard ground that is burrowed and contains shallow water fauna along with reworked material from the impact. These two thin layers are reported to be sandwiched between upper bathyal sediments (estimated as 300–400 m paleo-water depth) below and upper to middle bathyal sediments (estimated as 500–700 m water depth) above. The observations also accord with the expected result of a drawdown with possible subaerial exposure. Discussions with Michael Whalen (2019, personal communication) who was involved with IODP Expedition 364 acknowledged that the hardground could record subaerial exposure, with as much as 1 to 3 m.y. of time missing at the unconformity. The hiatus encompasses the same age as the incision at Yoakum and Chicontepec paleo-canyons. Likewise, an interpreted sequence boundary occurs beneath the reworked Paleocene sediments of the PETM level in the Yaxcopoil–1 well penetrating the Chicxulub impact crater (Fig. 1; Whalen et al., 2013).

In addition, in the U.S. margin, Sluijs et al. (2014) documented the 56 Ma unconformity beneath the PETM in the Harrell well and at the Red Hot Truck Stop outcrop in Mississippi (Fig. 1), where a 100,000 to 500,000 yr hiatus is believed to occur. In the Florida Straits, the research well Deep Sea Drilling Program (DSDP) Leg 77, Site 536 (Fig. 1) recorded a hiatus between at least 50–57 Ma where middle Eocene unconformably overlies upper Paleocene sediments (Shipboard Scientific Party, 1984). This well is in a deep part of the basin that may, or may not, have been subaerially exposed, but the hiatus may pertain to erosion caused by especially strong currents between the Gulf and the Proto-Caribbean, perhaps intensified by constriction from the Cuban Orogen, or by energetic refilling of the Gulf at the end of the drawdown.

Recently, Cossey et al. (2019, their p. 35–37) described the Acatepec Paleocene-Eocene section (Fig. 3) and possibly identified the first known outcrop occurrence of strata deposited during

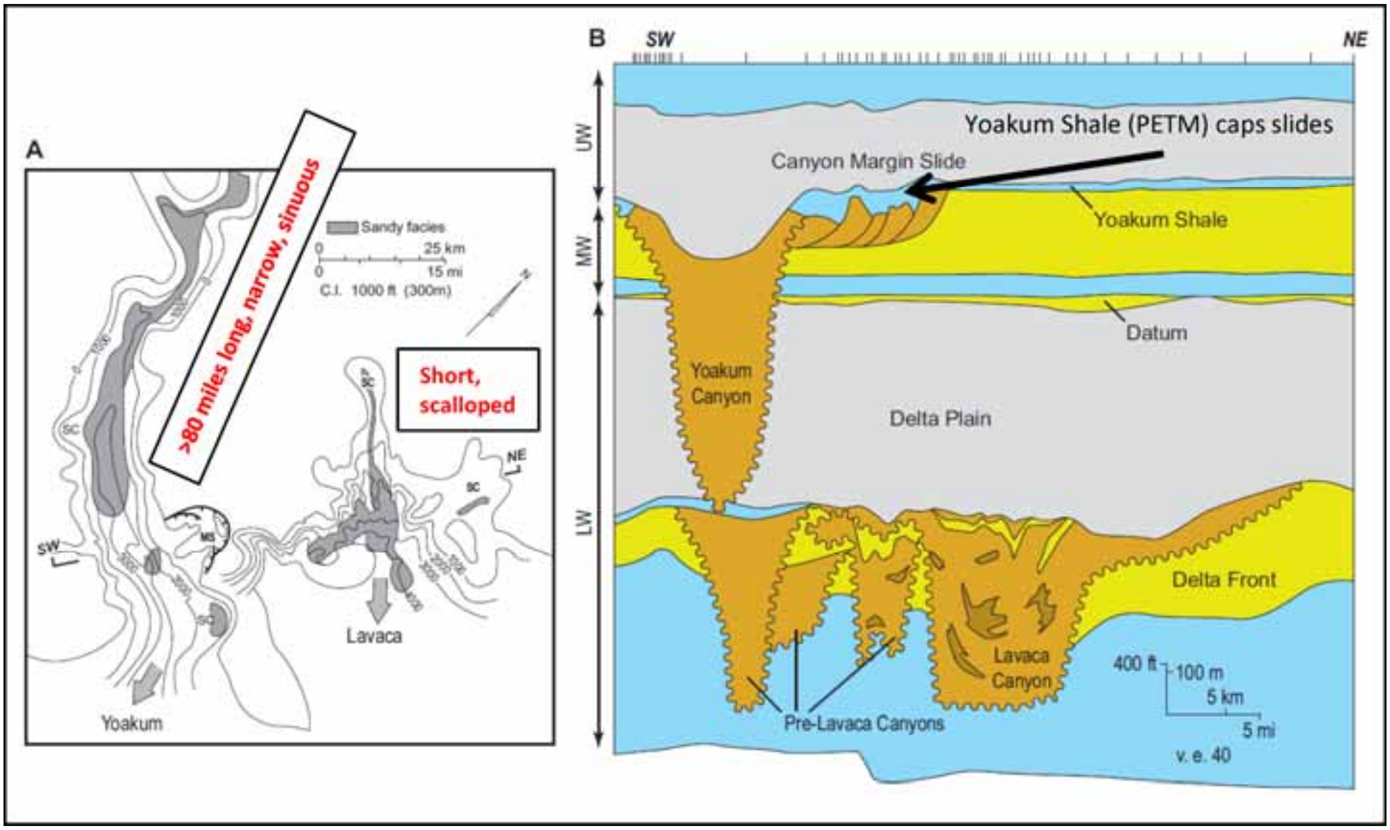

Figure 6. (A) Map and (B) cross-section showing the age and character differences between the Yoakum and Lavaca paleo-canyons in Texas, apparently formed by different processes (modified after Snedden and Galloway, 2019). Yoakum paleo-canyon was formed just prior to the PETM at about 56 Ma.

the PETM in eastern Mexico. The 40 m thick suspected PETM section contains an *Apectodinium* spp. acme and overlies the 56 Ma unconformity and was recently confirmed to contain a negative $\delta^{13}C$ signature, although not as “classic” a signature as other localities around the Gulf of Mexico (Cossey et al., 2019).

Another outcrop of the PETM is interpreted to exist near Bastrop, Texas, U.S.A., where the PETM has been interpreted as a “dark band”, bounded above and below by a hiatus and an erosional surface (Demchuk et al., 2019). These authors speculate that the larger of the two hiatuses may be above the PETM, but with such limited age control it could easily be below and equivalent to the 56 Ma sequence boundary.

4. MAGNITUDE OF THE DRAWDOWN

Accepting the subaerial erosion interpretation of Cossey et al. (2016, 2019), a minimum magnitude of the drawdown just before 56 Ma of perhaps 900–1300 m can be estimated by adding 200–600 m in order to subaerially expose upper bathyal seafloor in eastern Mexico (Cossey et al., 2019), and up to 700 m more to expose the bases of the paleo-canyons to fluvial incision. Alternatively, if we estimate the amount of stratigraphy that has been eroded along the thalweg of the Chicontepec paleo-canyon then a drawdown approaching 2.5 km might be contemplated. In addition, Rosenfeld (2020) estimated an approximate 2000 m drawdown derived from the erosional level of canyons along both the Florida and Yucatán escarpments, erosion of the Florida Straits paleo-canyon, and the paleo-depth of karsting on the Tuxpan Platform. Horbury et al. (2003) stated that evidence for karstification as deep as at least 1 km is seen in the geology of the Tuxpan Platform and other platforms and conclude that there has been freshwater diagenesis of the El Abra reservoirs, presumably prior to the migration of hydrocarbons into them.

Horbury et al. (2003) reported that, in the Faja de Oro–2 well (Fig. 1) (not the Faja de Oro–1 well which was miscited in Horbury et al., 2003), the matrix of the Tuxpan Platform karst contains planktonic foraminifera as young as middle Paleocene (P3 to P4) age in a breccias from core taken about 1000 m below the top of the platform. Pemex biostratigraphers (2019, personal communication) have also reported from the same well both Maastrichtian and Paleogene planktonic foraminifera as young as early Ypresian (early Eocene) in a breccia about 1200 m below the top of the middle Cretaceous El Abra Formation. This implies karstification/infilling to at least 1200 m paleo-depth sometime prior to the early Eocene, and possibly at the Paleocene-Eocene boundary (56 Ma), such that the entire Tuxpan Platform could have been sitting above water level for a short time much like the foundations of Mediterranean islands during the Messinian event (Roveri et al., 2016). Here, we avoid siding with any specific magnitude from those mentioned above, but we note that all lines of approach appear to be far greater than typical eustatic fluctuations.

5. EROSION ALONG THE WESTERN FLORIDA AND NORTHERN YUCATÁN MARGINS

On the outer ramps and upper escarpments of western Florida there are abundant sinkholes in present-day water depths of up to 1200 m, as well as steep-walled erosional canyons with thalweg to canyon rim relief of up to 1500 m (Fig. 7). There are similar canyon incisions and sinkholes on the Yucatán Escarpment as well (Fig. 8). Post-Eocene sedimentation on these margins has been minimal. The Florida Escarpment canyons were ascribed to submarine sapping by Paull et al. (1990a) with an estimated minimum of 5 km of landward erosional retreat of the entire escarpment proposed by Paull et al. (1990b) based on the

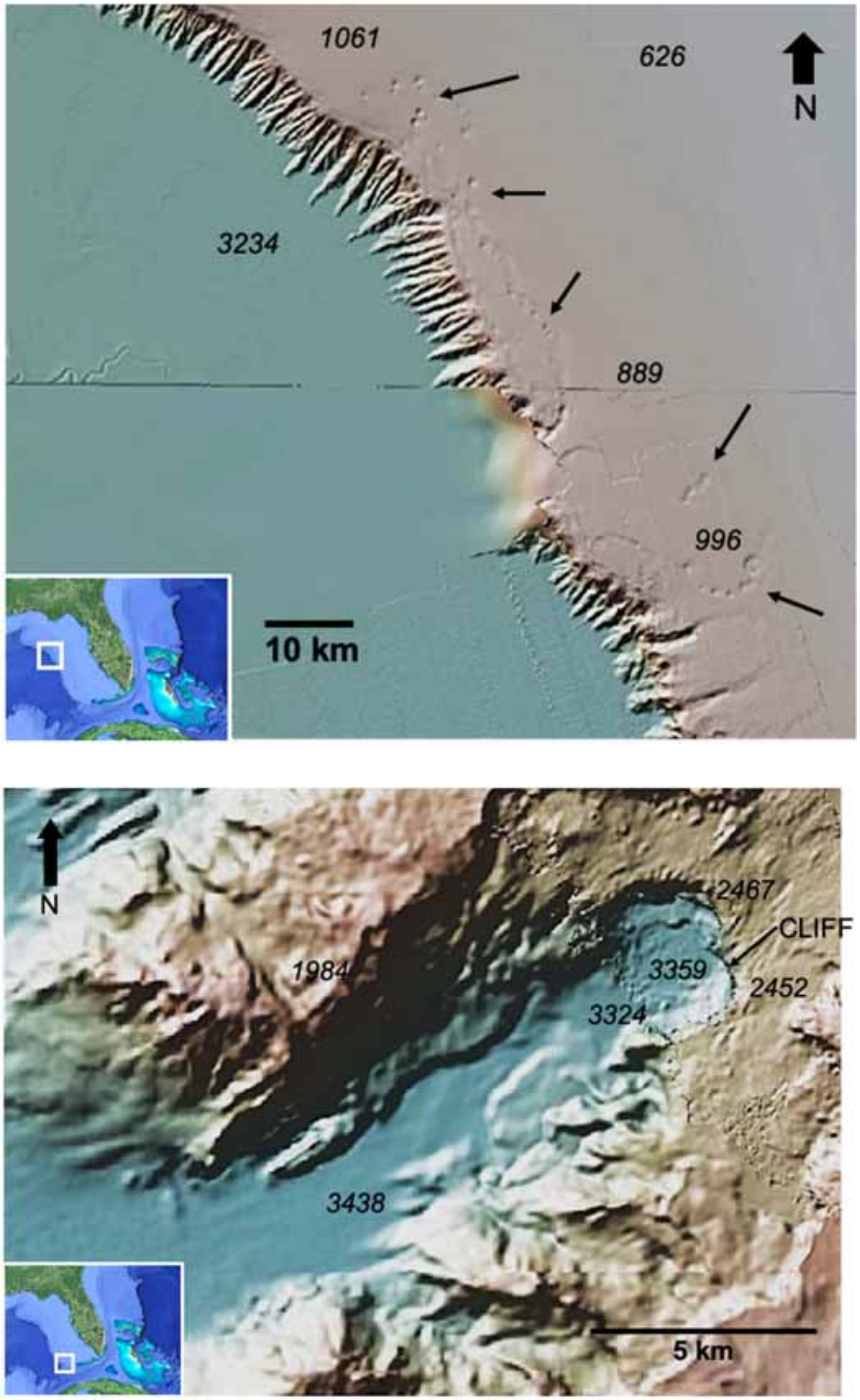

Figure 7. (Top) A portion of the West Florida Escarpment. Location is shown by white box in the inset. Italicized numbers are water depths in meters. Black arrows indicate trains of sinkholes. Note abundant canyons dissecting the escarpment. (Bottom)Florida Canyon is the largest canyon on the West Florida Escarpment. Location shown by white box in the inset. Italicized numbers are water depths in meters. Note the 900 m high cliff separating the upper from the lower canyon, with a 35 m deep "plunge pool" at its base. Thalweg to crest relief on the north wall of the canyon is 1500 m. Timing of incision is admittedly poorly constrained, but the smooth canyon floor that presumably buries the removed talus argues against Pleistocene slope failure. Images for both top and bottom are from the Polar Explorer web app, with inset images from Google Earth.

complete erosion of the Cretaceous marginal reef tract, leaving only inner margin facies exposed along the escarpments. The erosion of the original outer escarpment facies was considered by Snedden et al. (2020, p. 24) to be the result of "normal marine currents." Rosenfeld (2019) maintained that both sapping and marine currents have insufficient energy to remove the required large quantities of lithified carbonates. Rosenfeld (2019) proposed that the energy required to accomplish retreat of the Florida and Yucatán escarpments was provided by wave action during the drawdown lowstand, while the canyons were cut into the subaerially exposed escarpments by water pouring over the edges of the platforms. The Paleocene-Eocene karst surface under

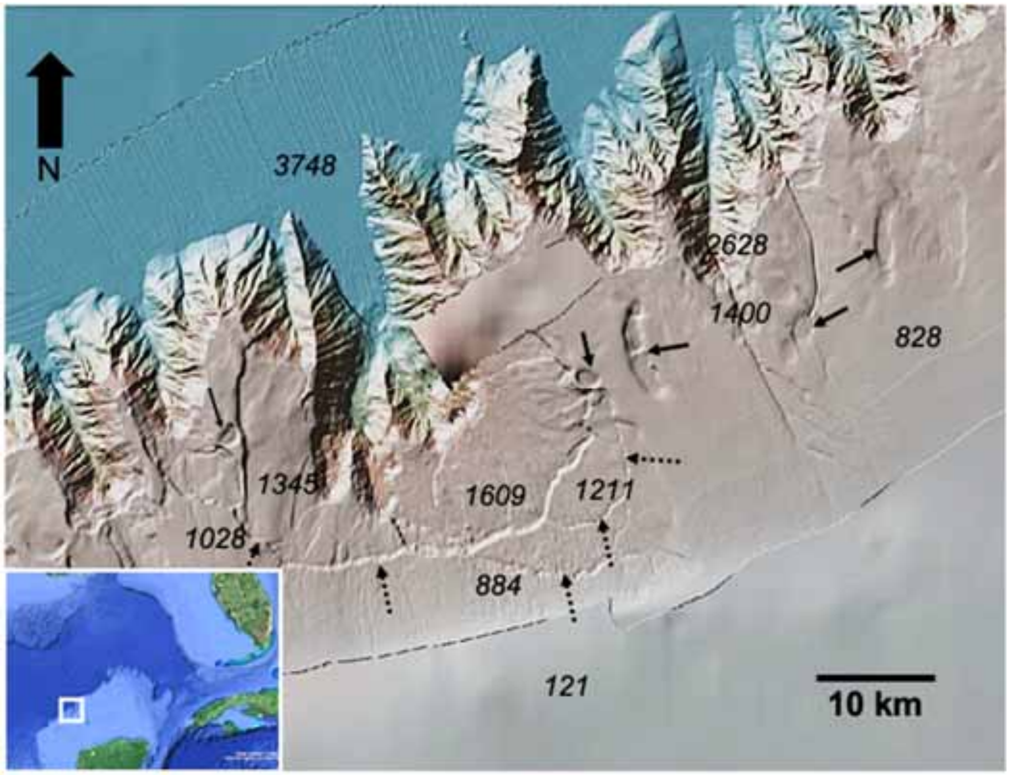

Figure 8. A portion of the Yucatán Escarpment. Location shown by white box in the inset. Italicized numbers are water depths in meters. Solid black arrows indicate sinkholes. Dashed black arrows indicate possible wave cut benches. Timing of incision is admittedly poorly constrained, but the smooth canyon floor that presumably buries the removed talus argues against Pleistocene slope failure. Image from Polar Explorer web app. Inset image from Google Earth.

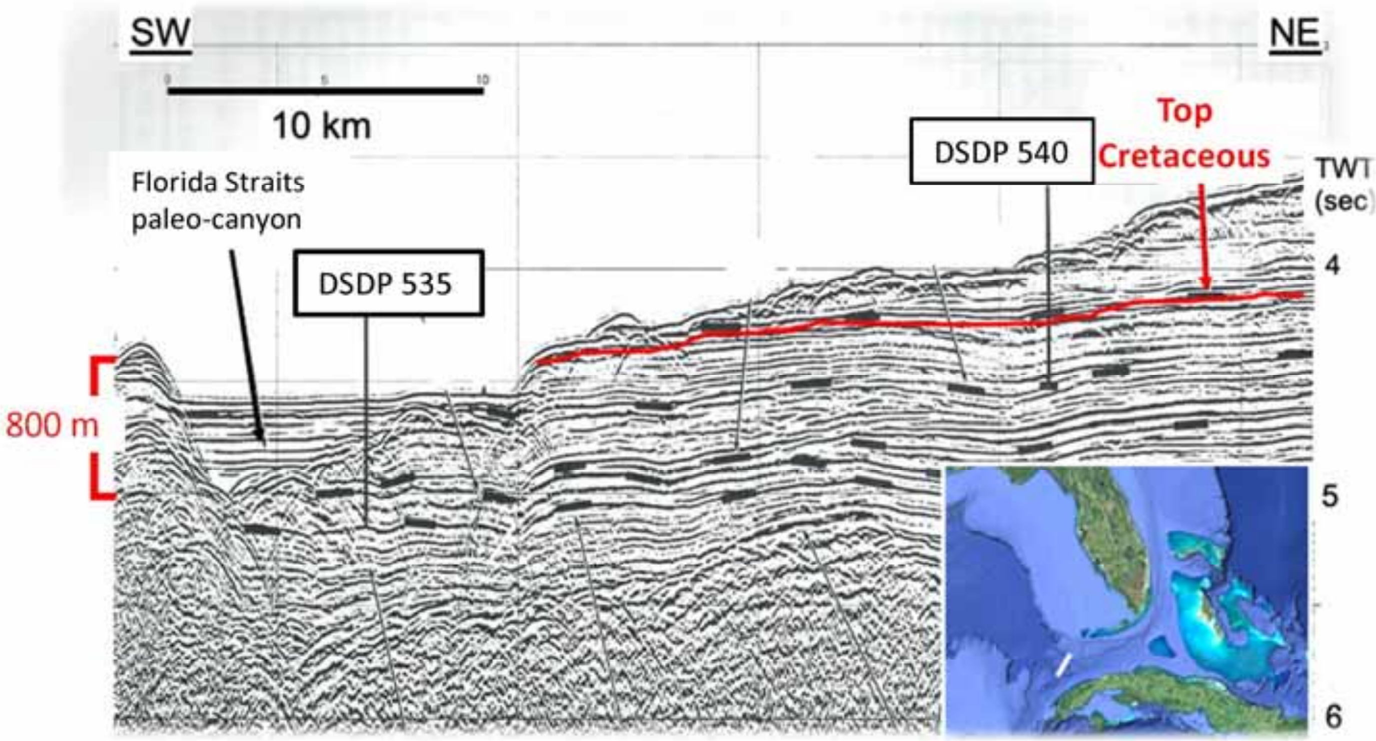

Figure 9. Seismic line across the western end of the Florida Straits paleo-canyon (modified after Buffler et al., 1984). Location shown by the white line in the inset. Note 800-meter relief from thalweg to top of canyon wall. DSDP 535 drilled Pleistocene sediments overlying mid-Cretaceous deepwater carbonates in the canyon but the oldest canyon fill sediments were not drilled.

much of South Florida, known as the "Boulder Zone" (Winston, 1995; Maliva et al., 2001), indicates that much of the Florida Platform could have been exposed at about the Paleocene-Eocene boundary.

The abundance and magnitude of the escarpment canyons of Florida and Yucatán are not seen along present-day carbonate-dominated continental margins which are generally constructional and not undergoing active erosion, such as the Great Barrier

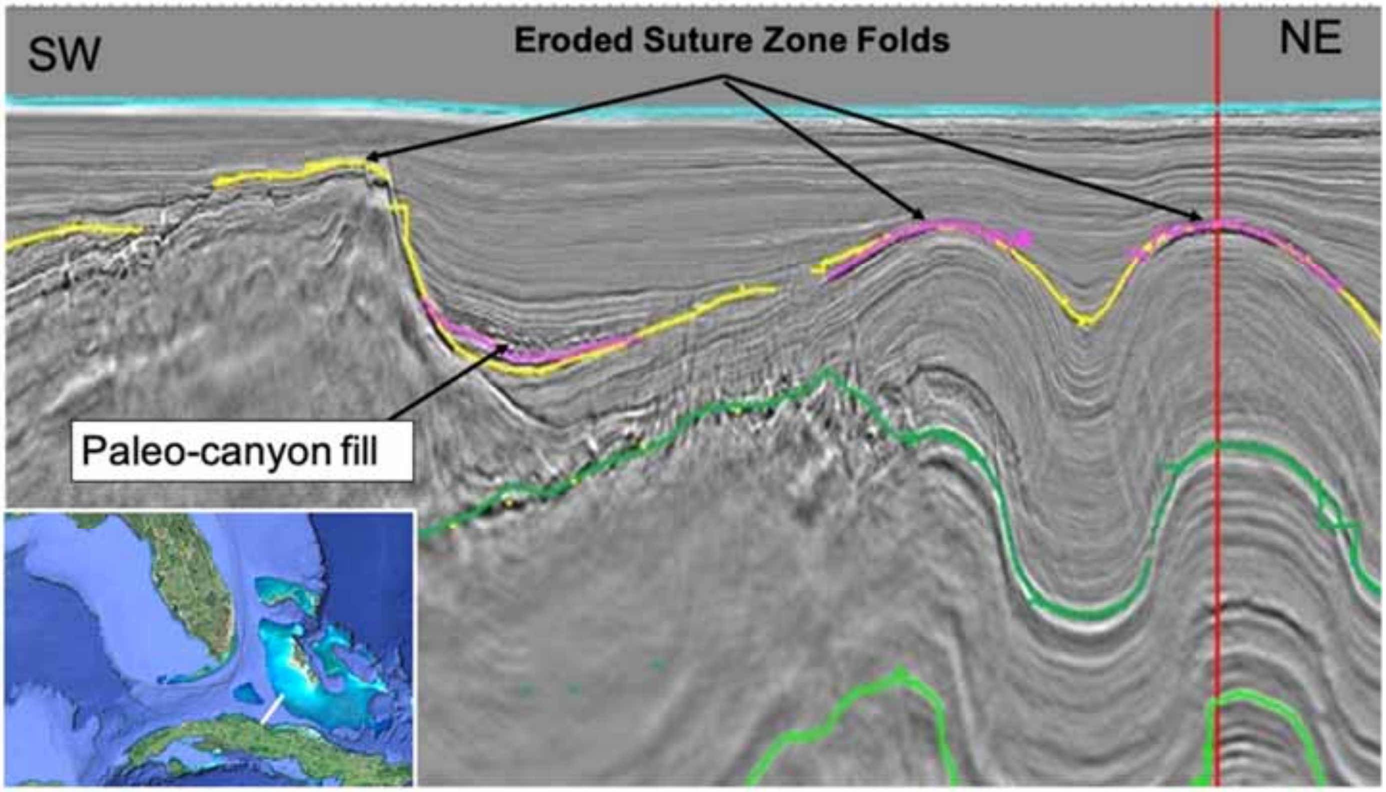

Figure 10. Seismic line across the Bahamas Channel between the Bahamas and Cuba. Location is shown by the white line in the inset. Note eroded folds and the partially filled paleo-canyon to the northeast of the prominent erosional escarpment. Seismic line modified from the Bahamas Petroleum Company website.

Reef of Australia, the eastern edge of the Florida Platform, and the Bahamas Platform. Along the southern margin of the Florida Platform (north side of the Florida Straits), there are very active marine currents but there is no undercutting of the margin. Instead, reefs are actively growing in the shallow water (Florida Keys) and active sedimentation is taking place in deeper water. This indicates the incapacity of most marine currents to remove lithified carbonates.

A further potential facet of the drawdown hypothesis is the presence of a deep erosional channel at the west end of the Cuba–Florida/Bahamas suture zone. Figure 9 shows an 800 m deep incision into Cretaceous basinal carbonates drilled by DSDP 535, named by Rosenfeld (2019) the Straits of Florida paleo-canyon. Farther east, seismic data available on the Bahamas Petroleum Company website crossing the Old Bahamas Channel between Cuba and the Bahamas reveals eroded anticlines ahead of the Cuban suture zone and a partially sediment filled paleo-canyon that must connect with the Straits of Florida paleo-canyon (Fig. 10). This extensive paleo-canyon system was proposed by Rosenfeld (2019) to be the main entry route for water that energetically refilled the Gulf and ended the drawdown(s).

6. FEASIBILITY THAT THE CUBA-BAHAMAS COLLISION ISOLATED THE GULF FROM THE WORLD OCEAN

Snedden et al. (2020) claimed that the Cuban Arc was too distant from the Bahamas Platform to have achieved Gulf isolation by the necessary time to explain Wilcox features outlined by Rosenfeld and Pindell (2003) as pertaining to drawdown. We wish to amend this claim by noting, firstly, that it is now the 56 Ma unconformity of greatest concern, rather than the 61 Ma Wilcox 4, or "Whopper" sandstone, that was originally considered. Thus, Cuba was about 100 km farther north at the key time than shown by Snedden et al. (2020). Secondly, the shallow Bahamas Bank and its crustal foundation are more generally believed to have extended some 150–200 km farther south than shown by Snedden et al. (2020), and now underlie almost the entirety of central Cuba (Pindell and Kennan, 2009; Pindell et al., 2020; Moreno-Toiran, 2003), hence the inclusion of the "Remedios" shallow-water platformal Mesozoic strata in the Cuban thrust belt (Fig. 1; Hempton and Barros, 1993). As suggested by Pindell (1985), the Mesozoic sections of western Cuba's Sierra de Guaniguanico were displaced from the eastern Yucatán margin by the Cuban Arc during oblique collision. This accretionary snow-plowing potentially formed a subaerial Yucatán–Guaniguanico–Cuban Arc connection during collision in western Cuba from 57 to 49 Ma as dated by overthrust flysch sections, according to Bralower and Iturralde-Vinent (1997). Less certain is whether the Central Cuban forearc and prism overthrusting the Remedios Belt rim of the southern Bahamas had achieved continuous subaerial connection with the Great Bank of the Bahamas and Florida, although a widespread "Eocene unconformity" is documented over most of the Great Bank and the Florida Straits (Sheridan et al., 1981; sections in Ladd and Sheridan, 1987). As considered by Rosenfeld and Pindell (2003) and argued by Pindell et al. (2005) and Pindell and Kennan (2009), drop off of the southwest-dipping North American slab almost certainly occurred as Cuba was accreted to the Bahamas, because the collision was driven by a westward-migrating North American Plate with a more stationary Cuban Arc. Hence, slab drop off was required in order for the Bahamas to continue moving west with the rest of the North American Plate. In turn, regional isostatic rebound centered along the trace of the suture as the slab dropped off may have been up to several km (Bercovici et al. 2015), greatly facilitating regional subaerial exposure and the tectonic isolation of the Gulf of Mexico. Figure 1 portrays a feasible reconstruction for 56 Ma.

7. DID THE GEORGIA CHANNEL SYSTEM PROVIDE A SECOND GATEWAY TO THE ATLANTIC?

One of the arguments against the Gulf drawdown has been the belief that a ~500 km long marine connection existed between the Gulf of Mexico and the Atlantic Ocean across northern Florida and Georgia in Paleocene-Eocene time (Fig. 1) such that the speculated Yucatán-Cuba-Bahamas-Florida subaerial barrier could not have isolated the Gulf. This region is called the Georgia Channel System and it consists of two separate features; the older Suwannee Channel and the younger Gulf Trough. The presence of the two spatially and temporally distinct channels is postulated to have resulted from a reduction and change in the direction of flow during the Late Paleocene (Huddlestun, 1993). The older Suwannee Channel (also known as the Suwannee Strait) (Fig. 1) is interpreted to be present from Late Cretaceous through early to middle Eocene (Huddlestun, 1993). This feature widens at the Atlantic and Gulf of Mexico ends, but narrows to about 60 km wide in the middle section. The younger Gulf Trough is interpreted to be an active channel from the early Eocene to Middle Miocene. Much has been previously published on the area (Mullins et al., 1986; Popenoe et al., 1987; Huddlestun, 1993; Huddlestun and Summerour, 1996; Jee, 1993, 1995) and an historical understanding of the Suwannee Strait is presented in Denne and Blanchard (2013, their p. 22–23).

Previous authors have switched between interpretations of erosional (Applin, 1952) and depositional (McKinney, 1984) origins for the Suwannee channel. McKinney (1984) noted that the channel separated carbonate facies banks to the south from terrigenous sediments in the north. Other workers in the area conclude that the Suwannee channel was not an effective barrier to north-south marine migrations (Burchard Carter, 2019, personal communication). The main conclusion from previous work is that the geological history and hydrodynamics of the area are not well understood. Presently, we are uncertain if the Georgia and northern Florida area comprised merely a shallow or an intermittent connection between the Gulf and the Atlantic during the Paleogene, with one of the intermittent bridges forming just before 56 Ma. We agree with Rosenfeld (2020) that the question of the Suwannee-Atlantic connection needs more work, especially the integration of high-resolution seismic data.

Equally important for our drawdown hypothesis is to establish if there was a continuous land barrier just before 56 Ma along the axis of the Florida Peninsular Arch, across the Florida Straits, into central and western Cuba, and over to the Yucatán, as speculated upon in Figure 1. Unconformities and karsted erosion surfaces along this corridor do exist (Winston, 1995), but current dating does not allow high-resolution correlation of unconformities, and therefore of a former land bridge, from Florida to Yucatán.

DISCUSSION

From the above, we conclude a Gulf-wide unconformity/hiatus occurs in shelf and bathyal sections of the offshore that dates to ~56 Ma, just before the PETM (55.8 Ma; Westerhold et al., 2018). This unconformity is coeval with paleo-canyon incision within the bathyal section and in places erodes on the order of 800 m of lithified rock (Fig. 4). Incision in the Chicontepec paleo-canyon, at least, appears to have been subaerial. The carbonate hardground with shallow water fauna and missing time at the Chicxulub impact ring also correlates, as does, perhaps more crudely, the deep karsting of the Mexican Tuxpan Platform and the canyons of the Florida and Yucatán escarpments. The amount of time represented by this hiatus is likely several hundred thousand years. The rapid fall and later rapid rise of the Gulf water level would not have allowed sufficient time for shallow water facies to develop and/or be preserved during the regression and transgression. The subsequent transgressive burial of this unconformity including paleo-canyon backfill defines the PETM in all sections noted herein. The apparent magnitude of this potential water level drop exceeds any possible eustatic fall, especially in the early Paleogene when continental glaciation is unlikely as a driver of eustatic cyclicity, as put forth in the introduction and papers in Pindell and Drake (1998).

Snedden et al. (2020) argued that Wilcox deposition occurred under normal marine conditions. We point out, however, that the timespan of the hypothesized drawdown need only have been about 5% of the overall approximately 11 m.y. of Wilcox time, and that the evidence points to a drawdown that left 3 to 4 km (1.9 to 2.5 mi) of water in the Gulf at all times. Thus, we too would expect essentially normal marine conditions to prevail in the deep Gulf throughout Wilcox time, and for the great majority of Wilcox time around the neritic and upper to middle bathyal rims, as well. It must be remembered that the deep central Gulf's sedimentary section has not been drilled and may hold important information unavailable at this time.

As alternative explanations for the observations noted for the paleo-canyons along eastern Mexico, namely subaerial exposure and erosion of bathyal section, we have contemplated several tectonic mechanisms including (1) flexural uplift with local "popping" of Laramide structures ahead of the Sierra Madre thrusting, (2) thermal uplift of the Sierra Madre foreland due to arc magmatism, (3) dynamic uplift associated with suspected Paleogene flattening of the Farallon subduction slab, (4) structural inversion along the continental flank of the offshore East Mexico (west Gulf of Mexico) Transform, and (5) isostatic unloading of the proximal margin by downslope slumping of the offshore Paleogene section. However, none of these tectonic mechanisms can explain both the short period and large magnitude of the observations noted herein.

Further against the idea of tectonic uplift driving paleo-canyon incision, Gray et al. (2001) concluded that most of the Tampico-Misantla Basin was undergoing burial until 40 Ma when the first signs of exhumation were detected, some 16 m.y. after the formation of the Chicontepec paleo-canyon system. On the other hand, Gray et al. (2020) show a HeFty model for an apatite fission track (AFT) analysis on a sample (ACAT17–1) from the Eocene Acatepec section within the Chicontepec Basin. HeFTy is a thermal history modeling program that yields time–temperature paths from complex thermochronological datasets. The software is able to provide with "forward models" (predict the expected data distribution for any given thermal history) and "inverse models" (finds the thermal histories that best matches some input data) functionalities (Ketcham, 2005; Ketcham et al., 2007, 2009). The inverse thermal model shown by Gray et al. (2020) for sample ACAT17–1 shows rapid cooling just prior to the Chicontepec incision (63–56 Ma), which could be taken as a record of rapid tectonic uplift for driving the incision. However, the pooled AFT age of ACAT17–1 (AFT age of 57.3 Ma) is indistinguishable with its early Eocene depositional age based both on published ages of the detrital zircons (maximum depositional age between 55.3 ± 1.0 Ma and 54.8 ± 1.4 Ma) and paleontology (Cossey et al., 2019), suggesting that the apatites do not record a pre–56 Ma exhumation history but rather had an origin contemporaneous with deposition (i.e., a volcanic origin). In fact, the Lower Eocene Acatepec section hosts conspicuous tuff layers interbedded with the clastic deposits corroborating the input of primary volcanic material. This leads us to believe that the Gray et al. (2020) presumption of rapid exhumation/uplift prior to paleo-canyon incision is potentially misleading. Here, we consider that the inferred Paleocene cooling in the ACAT17–1 thermal model does not represent tectonically driven exhumation of the source area. In our view, the apparent lower Eocene depositional age should be used as the starting point in the HeFty model. Subsequently, between 56 and about 42 Ma, we suggest the region experienced a moderate post-depositional heating caused probably by a combination of upper Chicontepec Formation burial (~3 km?) and hot fluids being evulsed from beneath the Sierra Madre thrust front into the Chicontepec foreland. This evulsion may also explain the formation of hypogene karsting seen at the top of the Acatepec measured section discussed in this paper and also described by Cossey et al. (2019). Further, this moderate heating to perhaps 90–100°C might explain the partially annealed fission track lengths observed in the ACAT17–1 sample. Thereafter, from just before 40 Ma, the sample was progressively exhumed with a relatively rapid pulse of exhumation in the Miocene, which ultimately led to today's subaerial exposure.

Zarra (2007), Zarra et al. (2019), and Winker (2007) have progressively improved the dating of the Wilcox sub-units. Due to these works, we have long abandoned the originally contemplated link between incision of the Chicontepec and Yoakum paleo-canyons with the deposition of the older Wilcox 4 (Berman and Rosenfeld, 2007) interval. The Wilcox 4 likely pertains, instead, to deflection of large Cordilleran rivers from Hudson's Bay to the Gulf, as suggested by Fred Ziegler's University of Chicago Paleogeographic Atlas Project 35 yr ago and greatly clarified by Galloway et al. (2011), Blum and Pecha (2014), and Blum et al. (2017), among others. However, this does not mean that Gulf drawdown did not cause the canyon incision dated to just before the PETM (about 56 Ma). To the contrary, the observations noted herein, and lack of further paleo-canyon formation around the Gulf until the Pleistocene glacial drawdown (Galloway et al., 1991), rather strongly suggest to us that a drop in water level at 56 Ma far larger than a eustatic drop remains an entirely viable concept worthy of continued study. Likewise, we see little reason why a rapid return of the Gulf to eustatic levels shouldn't provide a valid hypothesis for the 55.8 Ma drowning of all the sites mentioned herein and which is associated with the PETM.

The proposal of a drawdown far larger than a eustatic fluctuation but not severe enough to produce evaporites in the deep Gulf at 56 Ma should have implications for the greater Gulf deep basin, the sequence architecture of which is perhaps best summarized by Zarra et al. (2019). These authors break our four main sequences (Wilcox 1 to 4, spanning the age range of 51.1 Ma to 61.5 Ma) from top to bottom, with the famous "Whopper" sandstone comprising Wilcox 4. Although these authors saw no direct evidence for drawdown as envisaged by Rosenfeld and Pindell (2003) and relating to the Wilcox 4 interval, we judge here that the downdip correlative sequence of the 56 Ma unconformity in their designation is the lower of two cycles in their Wilcox 1B. Zarra et al. (2019) reported that:

- the base of the lower 1B cycle is estimated at 56.7 Ma and the top is at 55.8 Ma, or the PETM,
- the Wilcox 1 sequence (of four Wilcox sequences) comprises half the total Wilcox sediment volume in the Western Wilcox Trend, and a quarter to a third of the Inner and Outer Wilcox trends (Fig. 1), and
- Wilcox 1B accounts for 90% of the Wilcox 1 sediment volume in the Western Trend, and 85% of the Wilcox 1 volume in the Inner and Outer trends.

Thus, the Wilcox 1B, lasting only 900,000 yr in the dating scheme of Zarra et al. (2019), comprises about 45% and 25% of the total volume in all four Wilcox intervals in the Western and Inner/Outer trends, respectively. Unfortunately, Zarra et al. (2019) do not give the relative volume proportions of the lower versus the upper Wilcox 1B cycles. Nevertheless, the amount of sand-rich material that entered the Gulf at 56 Ma is striking.

Cossey et al. (2016) suggested that the rapid subaerial exposure of the vast upper continental margins around the Gulf might have triggered the PETM, by the wholesale pressure release of hydrocarbon gases and liquids (melting of methane clathrates) and the rupturing of conventional hydrocarbon traps by the removal of aqueous and sedimentary overburden. No one can say if this is true or not, and neither do we know the exact duration of possible subaerial exposure prior to the flooding event that was associated with the PETM. However, in terms of timing it appears that one (drawdown) could have led immediately to the other (PETM). We note that at this time there is no generally accepted trigger for the PETM. If the drawdown hypothesis becomes more widely accepted, it will be increasingly tempting to consider the temporal relationship between the drawdown and the PETM as more than coincidence. If the relationship is validated, then the numerous thermal oscillations that continued into the early Eocene (Westerhold et al., 2018) might suggest that marine isolation at the Cuba-Bahamas suture continued intermittently for more than a single event.

THE NEED FOR FURTHER WORK

With questions and possibilities as significant as those raised here, along with the radical proposal by Higgs (2009) that the Gulf might have become a giant brackish lake where fluvial input exceeded evaporation while isolated by the Cuba-Bahamas collision, we believe further studies are needed to test and validate the drawdown hypothesis in the Gulf of Mexico. This paper assimilates information from a variety of sources that suggests attention should be focussed on the 56 Ma sequence boundary as the most likely time of drawdown, probably just before the PETM. Some specific topics of further study might include:

(1) better documenting the Paleogene history of Gulf-Atlantic oceanographic connection at the Suwannee Strait;
(2) better defining the timing of events in the De Soto paleo-canyon, and establishing a possible source-to-sink relationship between the Suwannee Strait and the carbonate slope deposit within that paleo-canyon;
(3) evaluating whether the 56 Ma unconformity/hiatus at and around the Chicxulub impact site might be best explained in terms of subaerial exposure (drawdown, essentially a drastic type–1 sequence boundary) as suggested by the evaporites in the UNAM–6 well that lie outside the impact ring crater, rather than merely as a type–2 (submarine) sequence boundary;
(4) a sequence-stratigraphic and paleoenvironmental analysis of the Chicontepec Formation in the Tampico-Misantla Basin, considering the 56 Ma and other levels as possibly marking subaerial exposure, of which the same could be done for the subsurface paleo-canyons in Texas and Louisiana;
(5) detailed examination of modern seismic data with well control of the Florida Straits to see if a regional 56 Ma unconformity exists and if the Straits of Florida paleo-canyon is a giant plunge pool similar to that at the Straits of Gibraltar in the Mediterranean (Garcia-Castellanos et al., 2009);
(6) evaluation of modern seismic data and wells in the Cuban collisional suture zone and Bahamian foreland to determine the existence of a 56 Ma subaerial unconformity/hiatus connecting the Florida Peninsular Arch (the subsurface of onshore Florida) with central Cuba;
(7) detailed examination of the thalweg profile of the Chicontepec, Yoakum and other paleo-canyons and comparing them to fluvial *versus* submarine canyon profiles as discussed, for example, by Goren et al. (2014);
(8) study detailed bathymetry, if and when available, of the marine portions of the West Florida and Yucatán Platforms in order to define drainage patterns in the areas above the escarpments;

(9) regional studies of water salinities and fauna in the Eocene versus the Paleocene of the Gulf of Mexico and Tampico-Misantla basins; and
(10) study the characteristics of buried paleo-canyons (e.g., Tomón; Table 1) around the margins of the Yucatán Platform; seismic data of these features exists, but is proprietary to Pemex.

CONCLUSIONS

This paper summarizes the present status and new observations relevant to the Gulf of Mexico drawdown hypothesis proposed by Rosenfeld and Pindell (2003). We highlight observations that might best be explained by a drawdown, and harder to explain otherwise, such as:

(1) reported Paleogene evaporites in a well in the Yucatán Peninsula, Mexico;
(2) differing water salinities between the Paleocene and Eocene stratigraphy in the Gulf Basin;
(3) at least 19 paleo-canyons around the Gulf of Mexico rim, which appear to have been formed at the same time, and the longest of which is the Chicontepec paleo-canyon with features atypical of a submarine canyon;
(4) bitumen and paleosols preserved within upper bathyal depositional sequences in two outcrop sections in the Chicontepec Basin;
(5) approximately 2500 m of missing (eroded) stratigraphy in the thalweg of the Chicontepec paleo-canyon of eastern Mexico;
(6) hypogene karsting in the Chicontepec Basin formed by the expulsion of large amounts of water from the basin during the Eocene;
(7) potential correlation of a type–1 sequence boundary at 56 Ma just before the PETM in several locations around the Gulf rim and even in deepwater wells;
(8) clinoforms in southeastern Texas preserved 5 km basinward of the contemporaneous shelf-edge during the early Eocene;
(9) at least a 7 m.y. hiatus in the Florida Straits where the middle Eocene overlies the Paleocene;
(10) abundant sinkholes and the heads of steep-walled canyons with possible plunge pools at the present-day shelf edges of the western Florida and Yucatán escarpments;
(11) a revised ~56 Ma reconstruction of the northern Proto-Caribbean that shows potential isolation of the Gulf of Mexico by the collision of the Cuban Arc with the Bahamas; and
(12) the Upper Wilcox (Wilcox 1A and 1B) sequences in the deep Gulf contain an extremely high and disproportionate volume of sediment for their time spans.

The points above are all consistent with a short-lived (<1 m.y.) drawdown in the Gulf of Mexico on the order of 900 to 1300 m (and possibly over 2000 m) at approximately 56 Ma, far larger than any eustatic fluctuation, but not enough to promote regional evaporitic deposition. Current interpretations of the 500 km long Suwannee Channel of Georgia and northern Florida are inconsistent and do not disprove a continuous land bridge from Georgia to Florida for parts of the Paleogene. More studies with specific attention on the Paleocene-Eocene transition will hopefully resolve this issue.

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